



Using MMX™ Instructions to Implement Bilinear Interpolation of Video RGB Values

Information for Developers and ISVs

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1.0 INTRODUCTION

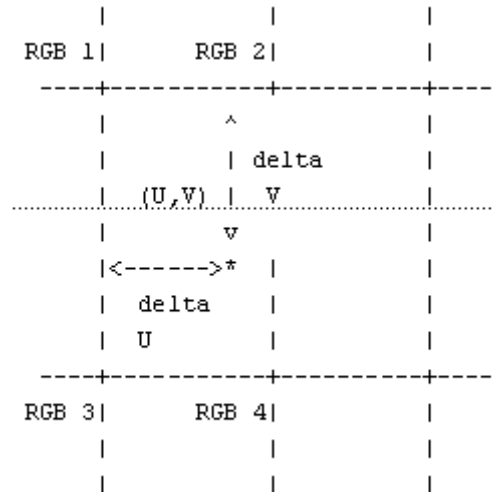
The media extension to the Intel Architecture (IA) instruction set includes single-instruction multiple-data (SIMD) instructions. This application note presents examples of code that use the new MMX instructions, PMULH, PSRLD and PADDW to perform a bilinear interpolation of RGB values. The performance improvement over traditional IA code is primarily due to the significantly faster MMX technology multiply instructions. These new instructions are faster because MMX technology allows multiple 16-bit multiplies in parallel. While the IA multiply instruction (IMUL) takes 11 cycles for a 16-bit multiply on a Pentium® processor, the MMX technology multiply instruction (PMULH) can perform four 16-bit multiplies with a throughput of only one cycle, with a three cycle latency.

2.0 BILINEAR INTERPOLATION

A common technique used for 3D rendering is to decompose the surface of objects into a large number of nearly planar triangles or rectangles. Their position in three-dimensional space is then mapped to the 2D display surface, and the individual triangles or rectangles drawn one pixel at a time. One technique for increasing the realism of the drawn image is to copy these triangles or rectangles from a bitmap image. These bitmaps are often called texture maps, since they are commonly used to represent texture-rich images such as wood grains.

This application note discusses one aspect of this process: accurately determining the color to display at a single pixel on the display surface. Prior to calling this code, it is assumed that the 3D software has calculated the position within the texture map that corresponds to the pixel to be drawn. In this application note, we assume that this position is calculated with fixed-point arithmetic (as opposed to floating-point). For information about using MMX instructions to implement this calculation, see *Using MMX™ Instructions to Implement Bilinear Interpolation of Video RGB Values*, Application Note AP-541, (Order Number 243026). The texture map position of the source pixel is traditionally described in (u,v) coordinates, where the integer part of (u,v) denotes a pixel that is physically stored in the texture bitmap. The fractional parts of u and v represent displacements to positions in the texture in between pixels that are physically stored in the texture bitmap (see Figure 1).

Figure 1. Bilinear Interpolation of RGB Color at Pixel (u,v)



Bilinear interpolation uses a simple formula to estimate the color that would have been at the computed (u,v) coordinates if the texture map had been stored at a higher spatial resolution. Thus, bilinear interpolation can be interpreted as a time/space tradeoff. It allows the application to use smaller texture bitmaps, thus reducing storage space, at the cost of some extra computation time to do the bilinear interpolation. With MMX technology optimization, the cost of the computation time to perform the bilinear interpolation is significantly reduced. The bilinear interpolation formula is:

$$R_result = R1 * (1 - dU) * (1 - dV) + R2 * (dU) * (1 - dV) +$$

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```
R3 * (1 - dU) * (dV) +  
R4 * (dU) * (dV)  
G_result = G1 * (1 - dU) * (1 - dV) +  
G2 * (dU) * (1 - dV) +  
G3 * (1 - dU) * (dV) +  
G4 * (dU) * (dV)  
B_result = B1 * (1 - dU) * (1 - dV) +  
B2 * (dU) * (1 - dV) +  
B3 * (1 - dU) * (dV) +  
B4 * (dU) * (dV)
```

3.0. THE MMX-BILINEAR INTERPOLATION PROCEDURE

This section describes the MMX-BilinearInterpolate procedure.

3.1. Format of the Procedure Parameters

The parameters of the MMX-BilinearInterpolate procedure are: a pointer to a texture map, TextureMap; a pointer to a color lookup table, ColorLookupTable; combined u/u value; combined v/v values; and a pointer to the return RGB value

The TextureMap array is a two-dimensional array of 8-bit indexes into the ColorLookupTable MMX-BilinearInterpolate expects the TextureMap array to be padded to 128 in the y dimension. When this padding is done, address calculations involving two-dimensional indexing into TextureMap can be performed by a simple left shift by 7 rather than by a multiply. For convenience, the example in this application note hard codes this value. A few simple changes to the code would allow this value to be passed as parameter.

The procedure also expects that the RGB values in the ColorLookupTable have been formatted as a quadword; where R, G, and B, values have been placed into the upper 8 bits of the 16-bit field. The range of RGB values is from binary 0 to 0xff00. Since the MMX technology PMULH instruction operates on signed numbers, these values are expected to be in the binary range 0 to 0x7f10. Typically, color lookup tables are small and rarely initialized, so preformatting them in this fashion as part of an application's outer loop is not expensive and greatly improves the efficiency of the bilinear interpolation procedure.

The parameters u/u , and v/v should each be formatted as an unsigned long-word, where the upper 10 bits is the u (or v) value, and the lower 22 bits is the u (or v) value. This is a typical format, because it allows efficient calculation of the position of the source pixel in the texture map, and supports texture maps up to 1024 pixels wide (a practical upper limit). The procedure extracts the u and v values by extending the 10-bit u and v values to 16 bits. The delta values are extracted by keeping the 16 most significant bits, resulting in unsigned binary values in the binary range of 0 to 0xffff. However, as discussed above, the MMX technology PMULH instruction operates on signed numbers rather than unsigned numbers. After extracting the values from the 32-bit long-word into 16-bit quantities, the procedure scales them to a binary range of 0 to 7ffff.

3.2. The Bilinear Interpolation Algorithm

There are three MMX technology multiply instructions, PMADD, PMULH, and PMULL. The PMADD instruction results in a 32-bit quantity, the PMULH and PMULL high each result in 16-bit quantities, but they keep only the upper or lower 16 bits respectively of the actual 32-bit result. Examination of the possible range of the input values to the procedure showed that using the PMULL instruction and keeping the upper 16 bits of a multiply result kept enough precision to produce correct final RGB results, as long as the color lookup table's RGB values were formatted to exist (scaled) in the upper 9 bits of the 16-bit RGB format (as discussed above).

The MMX technology multiply instructions perform multiplies on 16-bit data. The packed multiply and add instruction (PMADD) performs a multiply/accumulate operation by multiplying 16 by 16 bits into a 32-bit result that is added into a 32-bit accumulated value. The packed multiply high and packed high low

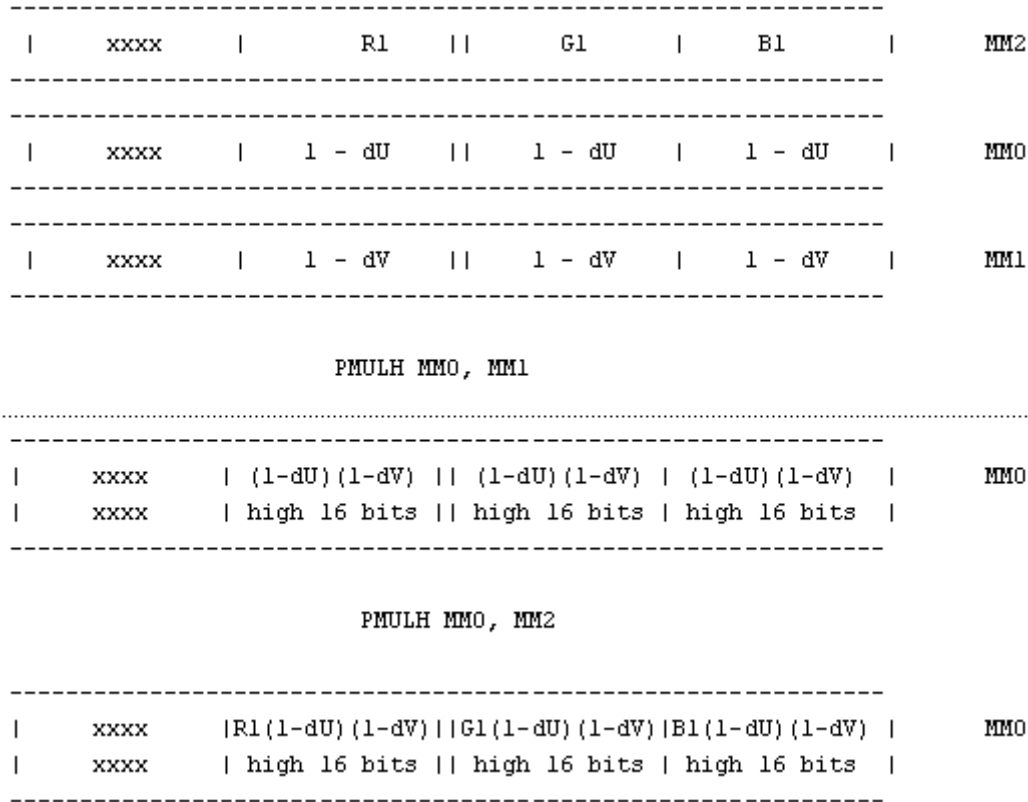
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instructions (PMULH and PMULL respectively) multiply 16 by 16 bits into a 32-bit result, but keep only 16 bits; PMULH keeps only the high order 16 bits, and PMULL keeps only the low order bits.

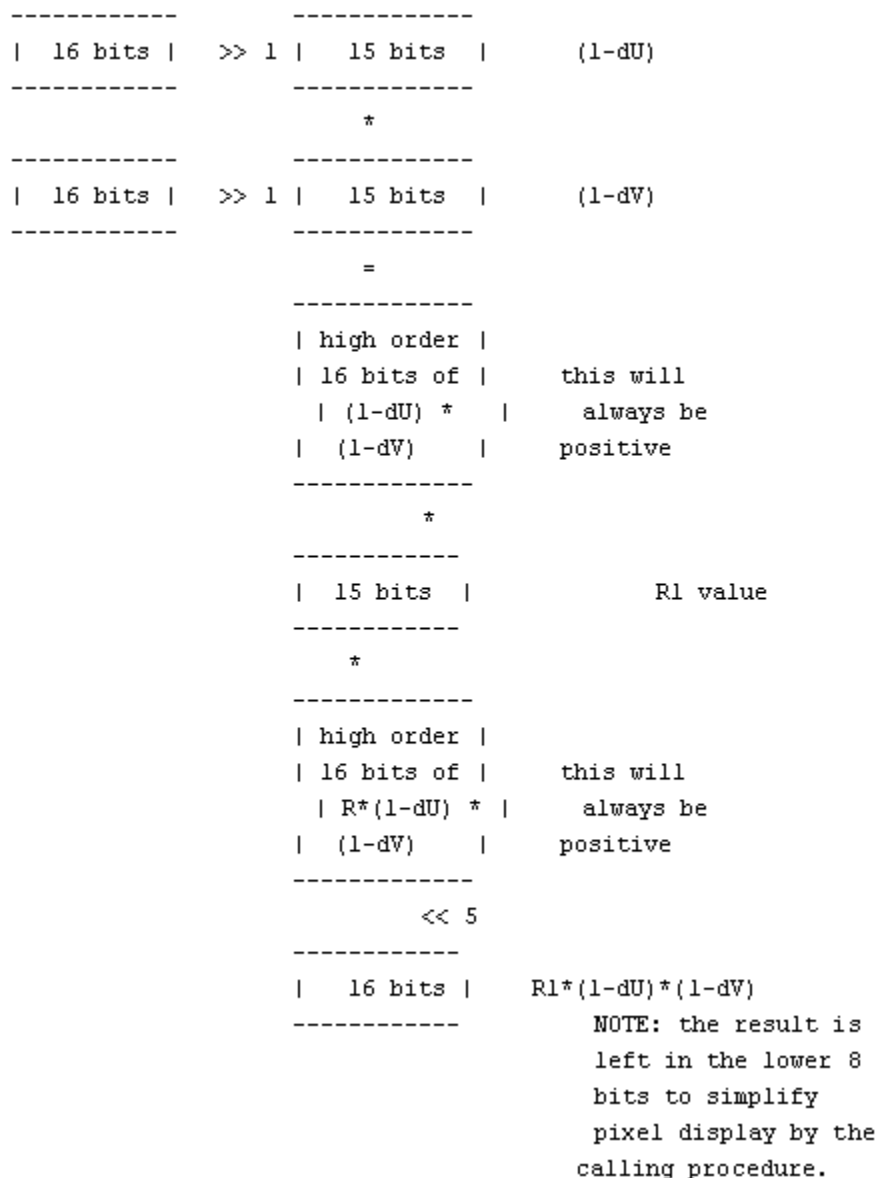
The MMX technology multiply instructions all multiply each 16-bit word in an MMX register in parallel. However, the PMADD instruction results in 32-bit double words, which allows only two multiplies in parallel. The PMULH and PMULL instructions result in 16-bit words, so when using one of these instructions it is possible to perform up to four multiplies in parallel. An example of register packing used in the MMX-BilinearInterpolate procedure is shown in Figure 2.

Figure 2: MMX™ Register Packing



The (1-u) term should be calculated as (0x8000 - u), but in order for the (1 - u) values to always be positive, (1-u) and (1-v) are calculated as (0x7fff - u). The scaling and multiply flow for the (1-u) * (1-v) term is shown in Figure 3. Using register packing and multiply flow allows the R, G, and B terms to be calculated in two multiplies, meaning that the entire bilinear interpolation formula takes only eight multiplies. In contrast, using the IA IMUL instruction to perform the bilinear interpolation requires 24 multiplies. Note that the resulting RGB remain in the lower 8 bits of their respective 16-bit fields to simplify pixel display by the calling procedure.

Figure 3. Scaling and Multiply Flow for $R1*(1-dU)*(1-dV)$



3.2. Optimizing the Bilinear Interpolation Algorithm

An optimized version of the MMX-BilinearInterpolate algorithm is shown in Appendix A, and a scalar version is shown in Appendix B. Two major optimization issues in the MMX-BilinearInterpolate procedure were instruction pairing and register dependence, and the three cycle latency associated with the result of a PMULH instruction (if the result of a PMULH is used before three cycles, cycles are inserted while the processor waits for the result. We advise scheduling instructions that don't depend on the result of the PMULH during these otherwise lost cycles). The fact that MMX technology moves to and from memory can only be paired with MMX instructions that are register/register instructions, and

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that PMULH can only be paired with scalar instructions, causes some minor pairing issues. Consequently, some minor recoding was done to allow for greater instruction pairing.

The scalar version of the MMX-BilinearInterpolate (see Appendix B) took 95 cycles to complete. After optimization (see Appendix A), the procedure took 66 cycles to complete. This optimization is due almost entirely to careful instruction pairing and instruction ordering to avoid the three cycle penalty associated with the PMULH instruction. For comparison, Appendix C has a C language source code version that operates using 32-bit unsigned multiplies where possible. Using MSVC 2.2, global optimization, and optimization for speed, this C language version was compiled and measured to take 259 clocks to complete. Even accounting for the fact that the C language source might itself be optimized to allow for better code generation, the version of the MMX-BilinearInterpolate procedure will probably be over 100 percent faster. As mentioned above, most of this improvement is due to the fact that in the MMX-BilinearInterpolate algorithm, eight PMULH multiplies at effectively one cycle each are performed to obtain a result, in comparison to the 24 IMUL multiplies taking 10 cycles each that are performed in the code.

APPENDIX A: OPTIMIZED BILINEAR INTERPOLATION ALGORITHM

```
;
; 'C' function prototype:
;
; void
; MMx_BiLinearInterpolate (BYTE      TextureMap[][128],
;                          RGBQWORD  ColorLookupTable[],
;                          DWORD      dwUVal,
;                          DWORD      dwVVal,
;                          LPRGBQWORD lpRGBOut)
;
; Abstract:  this routine determines the bilinear interpolation of a RGB
;            value at (U,V) in a transformed space, given a pointer to the
;            original texture map, and a colorlookup table for that texture
;            map.
;
;            the texture map was converted for effeciency, from a
;            [58][72] byte array, to a [58][128] byte array with the
;            elements from [j][72] to [j][127] unused.
;
;            the color lookup table is a 256 element array, where each
;            element is a RGBQWORD (see below).
;
;            the U and V elements are formatted as 32-bit numbers where
;            the upper 10 bits are the integer portion, and the lower
;            22 bits are the fractional portion of the (U,V) point whose
;            color is being interpolated.
;
;            NOTE: the fractional delta values are scaled
;                   from 0 - 0xffff.
;                   scale them down
;                   to    0 - 0x7fff
;                   to avoid signed/unsigned multiply issues
;
;            the RGBQWORD is defined in 'C' as:
;
;            typedef struct {
;                WORD  wB;
;                WORD  wG;
;                WORD  wR;
;                WORD  wUnused;
;            } RGBQWORD, FAR *LPRGBQWORD;
;
;            the values in the ColorLookupTable have been pre-formatted so that the
;            values are in bits 7-15.
;
;            The intepolation can be depicted as:
```

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```
;          by calling procedure.
;
;
;Environment:
;   MASM 6.11D
;
;*****
;FUNCTION LIST:
;   (functions contained in this source module)
;
; MMX_BiLinearInterpolate()
;
;*****
.586
.MODEL FLAT, C
include iammx.inc
TAG      STRUCT 2t
          wB      WORD      ?
          wG      WORD      ?
          wR      WORD      ?
          wUnused WORD      ?
TAG      ENDS
RGBQWORD TYPEDEF      TAG
LPRGBQWORD TYPEDEF    FAR PTR TAG
.CODE
;-----
; location of local vars on the stack
SAVEESP      EQU DWORD PTR [esp+0]
RGB1         EQU DWORD PTR [esp+8]
RGB2         EQU DWORD PTR [esp+16]
RGB3         EQU DWORD PTR [esp+24]
RGB4         EQU DWORD PTR [esp+32]
QTEMP        EQU DWORD PTR [esp+40]
QTEMP1       EQU DWORD PTR [esp+48]
ENDOFLOCALS  EQU DWORD PTR [esp+56]
LocalFrameSize = 56
;*****
;
MMx_BiLinearInterpolate PROC PUBLIC,
    TextureMap      : PTR DWORD,
    ColorLookupTable : PTR DWORD,
    dwUVal          : DWORD,
    dwVVal          : DWORD,
    lpRGBOut        : PTR DWORD
;   push                                ; THE ASSEMBLER actually generates this
;   mov     ebp, esp                    ; THE ASSEMBLER actually generates this
    sub     esp, LocalFrameSize
    mov     SAVEESP, ebp                ;save original esp to restore in epilgue
    push    edx
    and     esp, 0fffffff8h            ;8-byte align start of local stack frame
    mov     eax, dwUVal                ; get dwUVal from parameter list.
    mov     edx, dwVVal                ; get dwVVal from parameter list.
    mov     esi, eax                   ; save dwUVal.
    push    ebx
    mov     ecx, edx                   ; save dwVVal.
    shr     eax, 22                    ; get integer portion of dwUVal
```

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```

    push    esi
    push    ecx
    and     esi, 3ffffffH
    shr     edx, 22                ; get integer portion of dwVVal
    and     eax, 0000ffffH        ; eax = 0, U
    shr     esi, 7                ; shift by 7 instead of 6 to provide the 0-
0x7fff scaling
    and     ecx, 3ffffffH
    shr     ecx, 7                ; shift by 7 instead of 6 to provide the 0-
0x7fff scaling
    mov     ebx, esi              ; ebx = 0, dU
    shl     edx, 7                ; edx=V*128; 128 is hardcoded pitch value
    push    edi
    shl     ebx, 16               ; ebx = dU, 0
    and     edx, 0000ffffH        ; edx = 0, V
    or      ebx, esi              ; ebx = dU, dU
    mov     edi, ecx              ; edi = 0, dV
    shl     edi, 16               ; edi = dV, 0
    mov     QTEMP, ebx           ;
    and     esi, 0000ffffH        ; esi = 0, dU
    or      edi, ecx              ; edi = dV, dV
    and     ecx, 0000ffffH
    mov     QTEMP+4, ebx
    mov     QTEMP1, edi
    mov     QTEMP1+4, edi
    movq    mm4, QTEMP            ; mm4 =  dU  |  dU  ||  dU  |  dU
    movq    mm5, QTEMP1           ; mm5 =  dV  |  dV  ||  dV  |  dV
    movq    mm1, mm4              ; mm1 =  dU  |  dU  ||  dU  |  dU
    mov     edi, 7ffffH
    mov     ebx, 7ffffH
    sub     edi, ecx              ; edi = 0, 1-dV
    sub     ebx, esi              ; ebx = 0, 1-dU
    mov     ecx, edi              ; ecx = 0, 1-dV
    mov     esi, ebx              ; esi = 0, 1-dU
    shl     ecx, 16               ; ecx = 1-dV, 0
    add     edx, eax              ; edx = U + V*128
    shl     esi, 16               ; esi = 1-dU, 0
    add     edx, TextureMap        ; edx = &TextureMap[U+V*128]
    or      edi, ecx              ; edx = 1-dV, 1-dV
    or      ebx, esi              ; ebx = 1-dU, 1-dU
    mov     QTEMP, edi            ;
    mov     cl, BYTE PTR [edx] ; bl = TextureMap[U+V*128]
    mov     eax, ColorLookupTable ; &ColorLookupTable[0]
    and     ecx, 000000ffH
    mov     QTEMP1, ebx           ;
    mov     QTEMP1+4, ebx         ;
    movq    mm6, QTEMP1           ; mm6 = 1-dU | 1-dU || 1-dU | 1-dU
    movq    mm3, mm4              ; mm3 =  dU  |  dU  ||  dU  |  dU
    mov     QTEMP+4, edi          ;
    lea     ecx, [eax+ecx*8]       ; ebx = &ColorLookupTable[bl]
    movq    mm7, QTEMP            ; mm7 = 1-dV | 1-dV || 1-dV | 1-dV
    movq    mm0, mm6              ; mm0 = 1-dU | 1-dU || 1-dU | 1-dU
    pmulhw  mm1, mm7              ; compute (dU) * (1 - dV)
    movq    mm2, mm6              ; mm2 = 1-dU | 1-dU || 1-dU | 1-dU
    pmulhw  mm0, mm7              ; compute (1 - dU) * (1 - dV)
    mov     bl, BYTE PTR [edx+1]  ; bl = TextureMap[U+V*128+1]
    pmulhw  mm2, mm5              ; compute (1 - dU) * (dV)

```

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```

    and     ebx, 000000ffh
    pmulhw  mm3, mm5                ; compute (dU) * (dV)
    pop     edi                    ;
    movq    mm4, mm0                ; mm4 = (1-dU)(1-dV)
    movq    mm5, mm1                ; mm5 = (dU)(1-dV)
    movq    mm0, [ecx]              ; mm0 =      xxxx      |      R1      ||      G1
|      B1
    movq    mm6, mm2                ; mm6 = (1-dU)(dV)
    lea     ebx, [eax+ebx*8]         ; ebx = &ColorLookupTable[b1]
    mov     cl, BYTE PTR [edx+128]   ; b1 = TextureMap[U+V*128+128]
;
;   NOTE: we leave the results in the lower 8 bits to simplify
;           the pixel display
;
;   by calling procedure.
;
    pmulhw  mm0, mm4                ; mm0 =      xxxx      | R1(1-dU)(1-dV) ||
;                                     ; G1(1-dU)(1-dV) | B1(1-dU)(1-dV)

    and     ecx, 000000ffH
    movq    mm1, [ebx]              ; mm1 =      xxxx      |      R2      ||
;                                     ; G2      |      B2

    movq    mm7, mm3                ; mm7 = (dU)(dV)
    pmulhw  mm1, mm5                ; mm1 =      xxxx      | R2(dU)(1-dV) ||
;                                     ; G2(dU)(1-dV) | B2(dU)(1-dV)

    lea     ecx, [eax+ecx*8]         ; ebx = &ColorLookupTable[b1]
    pop     esi
    mov     b1, BYTE PTR [edx+128+1] ; b1 = TextureMap[U+V*128+128+1]
    movq    mm2, [ecx]              ; mm2 =      xxxx      |      R3      ||
;                                     ; G3      |      B3

    psrlw   mm0, 5                  ;
    pmulhw  mm2, mm6                ; mm2 =      xxxx      | R3(1-dU)(dV) ||
;                                     ; G3(1-dU)(dV) | B3(1-dU)(dV)

    and     ebx, 000000ffH
    lea     ebx, [eax+ebx*8]         ; ebx = &ColorLookupTable[b1]
    psrlw   mm1, 5                  ;

    movq    mm3, [ebx]              ; mm3 =      xxxx      |      R4      |
;                                     ; ||      G4      |      B4

    paddw   mm0, mm1                ; mm3 = xxxx      | R4(dU)(dV) || G4(dU)(dV)
    pmulhw  mm3, mm7                ;
    psrlw   mm2, 5                  ;
    pop     edx                    ;
    pop     ecx                    ;
    paddw   mm2, mm0                ;
    psrlw   mm3, 5                  ;
    mov     eax, lpRGBOut
    paddw   mm2, mm3
    movq    [eax], mm2
    emms                                ; clear the FP stack
    pop     ebx                    ;
;   leave                                ; THE ASSEMBLER actually generates this
    ret     0                        ;
MMX_BiLinearInterpolate ENDP
END

```

APPENDIX B: SCALAR VERSION OF THE BILINEAR INTERPOLATION ALGORITHM

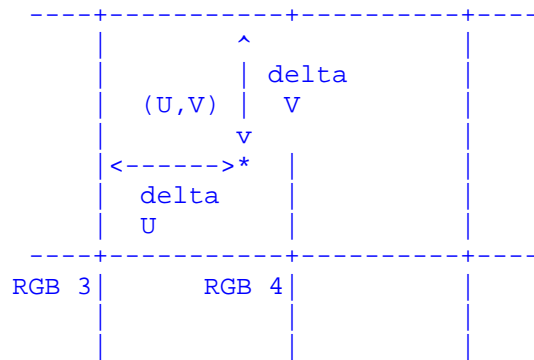
```

;
; 'C' function prototype:
;
; void
; MMx_BiLinearInterpolate (BYTE      TextureMap[][128],
;                          RGBQWORD  ColorLookupTable[],
;                          DWORD      dwUVal,
;                          DWORD      dwVVal,
;                          LPRGBQWORD lpRGBOut)
;
; Abstract: This routine determines the bilinear interpolation of a RGB
; value at (U,V) in a transformed space, given a pointer to the
; original texture map, and a colorlookup table for that texture
; map.
;
; The texture map was converted for effeciency, from a
; [58][72] byte array, to a [58][128] byte array with the
; elements from [j][72] to [j][127] unused.
;
; The color lookup table is a 256 element array, where each
; element is a RGBQWORD (see below).
;
; The U and V elements are formatted as 32-bit numbers where
; the upper 10 bits are the integer portion, and the lower
; 22 bits are the fractional portion of the (U,V) point whose
; color is being interpolated.
;
; NOTE: the fractional delta values are scaled
;       from 0 - 0xffff.
;       Scale them down
;       to 0 - 0x7fff
;       to avoid signed/unsigned multiply issues
;
; The RGBQWORD is defined in 'C' as:
;
; typedef struct {
;     WORD wB;
;     WORD wG;
;     WORD wR;
;     WORD wUnused;
; } RGBQWORD, FAR *LPRGBQWORD;
;
; The values in the ColorLookupTable have been
; pre-formatted so that the RGB values are in bits 7-15.
;
; The intepolation can be depicted as:
;
;
; RGB 1 | RGB 2 |

```

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```
R_result = R1 * (1 - delta U) * (1 - delta V) +
R2 * (delta U) * (1 - delta V) +
R3 * (1 - delta U) * (delta V) +
R4 * (delta U) * (delta V)
```

```
G_result = G1 * (1 - delta U) * (1 - delta V) +
           G2 * (delta U) * (1 - delta V) +
           G3 * (1 - delta U) * (delta V) +
           G4 * (delta U) * (delta V)
```

```
B_result = B1 * (1 - delta U) * (1 - delta V) +
           B2 * (delta U) * (1 - delta V) +
           B3 * (1 - delta U) * (delta V) +
           B4 * (delta U) * (delta V)
```

The computations are performed in 15 bits, with the multiplies resulting in 31/30-bits, with 16-bit precision being recovered at the final result. Note: the shifts are 'performed' by pmulh.

```

30 bits      15 bits      15 bits
result = (1 - delta U) * (1 - delta V)

```

then,

```
30 bits    15 bits
result = result >> 15
```

then,

```

31 bits    16 bits    15 bits
value      = R1      * result

```

then,

```
31 bits    16 bits
value  = value >> 15
```

NOTE: We leave the results in the lower 8 bits to simplify the pixel display by calling procedure.

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```
;
;Environment:
;   MASM 6.11D
;
;*****
;FUNCTION LIST:
;   (functions contained in this source module)
;
; MMX_BiLinearInterpolate()
;
;
;*****
.586
.MODEL FLAT, C
include iammx.inc
TAG      STRUCT 2t
          wB      WORD      ?
          wG      WORD      ?
          wR      WORD      ?
          wUnused WORD      ?
TAG      ENDS
RGBQWORD      TYPEDEF      TAG
LPRGBQWORD    TYPEDEF      FAR PTR TAG
;-----
; location of parameters on the stack
TextureMap      = 8
ColorLookupTable = 12
dwUVal          = 16
dwVVal          = 20
lpRGBOut        = 24
;-----
; location of local vars on the stack
RGB1            = -8
RGB2            = -16
RGB3            = -24
RGB4            = -32
QTEMP          = -40
.CODE
;*****
;
MMx_BiLinearInterpolate PROC PUBLIC
    push    ebp
    mov     ebp, esp
    sub     esp, 40                ; reserve space for locals.
    push    ebx
    push    ecx
    push    edx
    push    esi
    push    edi
;-----
; get fractional parts
; of U from the dwUVal parameter on
; the stack:
;
    mov     eax, dwUVal[ebp]        ; get dwUVal from parameter list.
    mov     esi, eax                ; save dwUVal.
    and     esi, 3ffffFH
```

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```

shr     esi, 7                ; extract bottom 22 bits from dwUVal.
                                ; (NOTE: we shift by 7 instead of 6
                                ; to provide the 0-0x7fff scaling)

and     esi, 0000ffffH        ; esi = dU
shr     eax, 22                ; get integer portion of dwUVal
and     eax, 0000ffffH        ; eax = U
mov     edx, dwVVal[ebp]       ; get dwVVal from parameter list.
mov     ecx, edx               ; save dwVVal.
and     ecx, 3ffffffH
shr     ecx, 7                ; extract bottom 22 bits from dwVVal.
                                ; (NOTE: we shift by 7 instead of 6
                                ; to provide the 0-0x7fff scaling)

and     ecx, 0000ffffH        ; ecx = dV
shr     edx, 22                ; get integer portion of dwVVal
and     edx, 0000ffffH        ; edx = V
shl     edx, 7                ; multiply the V value by 128,
                                ; to account for the pitch of
                                ; TextureMap[][128] array.
                                ; (edx = V*pitch.)

;-----
; build the multiply quadwords
mov     ebx, esi               ; ebx = 0, dU
shl     ebx, 16                ; ebx = dU, 0
or      ebx, esi               ; ebx = dU, dU
mov     QTEMP[ebp], ebx
mov     QTEMP[ebp+4], ebx      ;
movq    mm4, QTEMP[ebp]        ; mm4 =  dU   |  dU   ||  dU   |  dU
mov     ebx, 7ffffH
and     esi, 0000ffffH
sub     ebx, esi               ; ebx = 0, 1-dU
mov     esi, ebx               ; esi = 0, 1-dU
shl     esi, 16                ; esi = 1-dU, 0
or      ebx, esi               ; ebx = 1-dU, 1-dU
mov     QTEMP[ebp], ebx
mov     QTEMP[ebp+4], ebx
movq    mm1, mm4               ; mm1 =  dU   |  dU   ||  dU   |  dU
movq    mm6, QTEMP[ebp]        ; mm6 = 1-dU | 1-dU || 1-dU | 1-dU
mov     ebx, ecx               ; ebx = 0, dV
shl     ebx, 16                ; ebx = dV, 0
or      ebx, ecx               ; ebx = dV, dV
mov     QTEMP[ebp], ebx
mov     QTEMP[ebp+4], ebx
movq    mm5, QTEMP[ebp]        ; mm5 =  dV   |  dV   ||  dV   |  dV
movq    mm0, mm6               ; mm0 = 1-dU | 1-dU || 1-dU | 1-dU
mov     ebx, 7ffffH
and     ecx, 0000ffffH
sub     ebx, ecx               ; ebx = 0, 1-dV
mov     ecx, ebx               ; ecx = 0, 1-dV
shl     ecx, 16                ; ecx = 1-dV, 0
or      ebx, ecx               ; ebx = 1-dV, 1-dV
mov     QTEMP[ebp], ebx
mov     QTEMP[ebp+4], ebx
movq    mm7, QTEMP[ebp]        ; mm7 = 1-dV | 1-dV || 1-dV | 1-dV
movq    mm3, mm4               ; mm3 =  dU   |  dU   ||  dU   |  dU
pmulhw mm0, mm7               ; compute (1 - dU) * (1 - dV)
pmulhw mm1, mm7               ; compute (dU) * (1 - dV)
movq    mm2, mm6               ; mm2 = 1-dU | 1-dU || 1-dU | 1-dU

```

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```

    pmulhw    mm3, mm5                ; compute (dU) * (dV)
    pmulhw    mm2, mm5                ; compute (1 - dU) * (dV)
    movq      mm4, mm0                ; mm4 = (1-dU)(1-dV)
    movq      mm5, mm1                ; mm5 = (dU)(1-dV)
    movq      mm6, mm2                ; mm6 = (1-dU)(dV)
    movq      mm7, mm3                ; mm7 = (dU)(dV)
    add       edx, eax                ; edx = U + V*128
    mov       eax, ColorLookupTable[ebp]; &ColorLookupTable[0]
    add       edx, TextureMap[ebp]     ; edx = &TextureMap[U+V*128]
    ;-----
    ;
    ;   NOTE: We leave the results in the lower 8 bits to simplify
    ;   the pixel display by calling procedure.
    ;
    ;-----
    ; compute:
    ; R1 * (1 - dU) * (1 - dV)
    ; G1 * (1 - dU) * (1 - dV)
    ; B1 * (1 - dU) * (1 - dV)
    xor       ebx, ebx
    mov       bl, BYTE PTR [edx]      ; bl = TextureMap[U+V*128]
    lea       ebx, [eax+ebx*8]        ; ebx = &ColorLookupTable[bl]
    movq      mm0, [ebx]              ; mm0 =      xxxx      |      R1      ||
G1          |      B1
    pmulhw    mm0, mm4                ; mm0 =      xxxx      | R1(1-dU)(1-dV) ||
G1(1-dU)(1-dV) | B1(1-dU)(1-dV)
    psrlw     mm0, 5                  ;
    ;-----
    ; compute:
    ; R2 * (dU) * (1 - dV)
    ; G2 * (dU) * (1 - dV)
    ; B2 * (dU) * (1 - dV)
    xor       ebx, ebx
    mov       bl, BYTE PTR [edx+1]    ; bl = TextureMap[U+V*128+1]
    lea       ebx, [eax+ebx*8]        ; ebx = &ColorLookupTable[bl]
    movq      mm1, [ebx]              ; mm1 =      xxxx      |      R2      ||
G2          |      B2
    pmulhw    mm1, mm5                ; mm1 =      xxxx      | R2(dU)(1-dV) ||
G2(dU)(1-dV) | B2(dU)(1-dV)
    psrlw     mm1, 5                  ;
    ;-----
    ; compute:
    ; R3 * (1-dU) * (dV)
    ; G3 * (1-dU) * (dV)
    ; B3 * (1-dU) * (dV)
    xor       ebx, ebx
    mov       bl, BYTE PTR [edx+128] ; bl = TextureMap[U+V*128+128]
    lea       ebx, [eax+ebx*8]        ; ebx = &ColorLookupTable[bl]
    movq      mm2, [ebx]              ; mm2 =      xxxx      |      R3      ||
G3          |      B3
    pmulhw    mm2, mm6                ; mm2 =      xxxx      | R3 (1-dU)(dV) ||
G3(1-dU)(dV) | B3(1-dU)(dV)
    psrlw     mm2, 5                  ;
    ;-----
    ; compute:
    ; R4 * (dU) * (dV)
    ; G4 * (dU) * (dV)

```

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```

    ; B4 * (dU) * (dV)
    xor     ebx, ebx
    mov     bl, BYTE PTR [edx+128+1] ; bl = TextureMap[U+V*128+128+1]
    lea     ebx, [eax+ebx*8]         ; ebx = &ColorLookupTable[bl]
    movq    mm3, [ebx]               ; mm3 =      xxxx      |      R4      ||      G4
|
    B4
    pmulhw  mm3, mm7                 ; mm3 =      xxxx      |      R4(dU)(dV) ||
G4(dU)(dV) | B4(dU)(dV)
    psrlw   mm3, 5                   ;
    ;-----
    ; now add'm up...
    paddw   mm0, mm1
    paddw   mm2, mm3
    paddw   mm0, mm2
    ;-----
    ; save the result out into lpRGBOut
    mov     ebx, lpRGBOut[ebp]
    movq    [ebx], mm0
    ;-----
alldone:
                                ; restore stack
    pop     edi
    pop     esi
    pop     edx
    pop     ecx
    pop     ebx
    mov     esp, ebp
    pop     ebp
    emms
    ret     0
                                ; clear the FP stack
MMX_BiLinearInterpolate ENDP
END
```

APPENDIX C: BILINEAR INTERPOLATION ALGORITHM IN C LANGUAGE SOURCE CODE

Abstract: This routine determines the bilinear interpolation of a RGB value at (U,V) in a transformed space, given a pointer to the original texture map, and a colorlookup table for that texture map.

The texture map was converted for effeciency, from a [58][72] byte array, to a [58][128] byte array with the elements from [j][72] to [j][127] unused.

The color lookup table is a 256 element array, where each element is a RGBQWORD (see below).

The U and V elements are formatted as 32-bit numbers where the upper 10 bits are the integer portion, and the lower 22 bits are the fractional delta portion of the (U,V) point whose color is being interpolated.

NOTE: the fractional delta values are scaled
 from 0 - 0xffff.
 scale them down
 to 0 - 0x7fff
 to avoid signed/unsigned multiply issues
 (we do this in this 'c' code,
 Although it is really only an issue for the
 MMX assembly version, since MMX doesn't
 support unsigned multiplies.

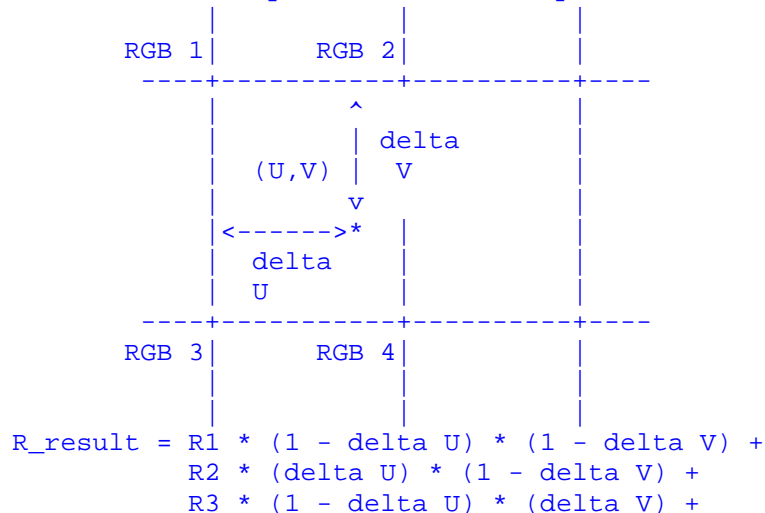
The RGBQWORD is defined as:

```
typedef struct {
    WORD wB;
    WORD wG;
    WORD wR;
    WORD wUnused;
} RGBQWORD, FAR *LPRGBQWORD;
```

The values in the ColorLookupTable have been pre-formatted so that the RGB values are in bits 7-15.

This routine returns as output, a RGBQWORD value into the LPRGBQWORD parameter

The intepolation can be depicted as:



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```

    R4 * (delta U) * (delta V)
G_result = G1 * (1 - delta U) * (1 - delta V) +
    G2 * (delta U) * (1 - delta V) +
    G3 * (1 - delta U) * (delta V) +
    G4 * (delta U) * (delta V)
B_result = B1 * (1 - delta U) * (1 - delta V) +
    B2 * (delta U) * (1 - delta V) +
    B3 * (1 - delta U) * (delta V) +
    B4 * (delta U) * (delta V)
Environment:  MSVC v2.2
*****
FUNCTION LIST:
    (functions contained in this source module)
*****/
#include <windows.h>
#include "bilin.h"
void
BiLinearInterpolate (BYTE      TextureMap[][128],
                    RGBQWORD   ColorLookupTable[],
                    DWORD       dwUVal,
                    DWORD       dwVVal,
                    LPRGBQWORD lpRGBOut)
{
    DWORD dwUDelta = (dwUVal & 0x003fffffL) >> 6;
    DWORD dwVDelta = (dwVVal & 0x003fffffL) >> 6;
    DWORD dwUInt   = dwUVal >> 22;
    DWORD dwVInt   = dwVVal >> 22;
    RGBQWORD RGB1 = ColorLookupTable[TextureMap[dwVInt][dwUInt]];
    RGBQWORD RGB2 = ColorLookupTable[TextureMap[dwVInt][dwUInt + 1]];
    RGBQWORD RGB3 = ColorLookupTable[TextureMap[dwVInt + 1][dwUInt]];
    RGBQWORD RGB4 = ColorLookupTable[TextureMap[dwVInt + 1][dwUInt + 1]];

    WORD w1, w2, w3, w4;
    DWORD dwTemp1, dwTemp2, dwTemp3, dwTemp4;
    dwTemp1 = (0x10000L - dwUDelta) * (0x10000L - dwVDelta);
    dwTemp2 = dwUDelta * (0x10000L - dwVDelta);
    dwTemp3 = (0x10000L - dwUDelta) * dwVDelta;
    dwTemp4 = dwUDelta * dwVDelta;
    dwTemp1 = dwTemp1 >> 16;
    dwTemp2 = dwTemp2 >> 16;
    dwTemp3 = dwTemp3 >> 16;
    dwTemp4 = dwTemp4 >> 16;
    // compute B
    w1 = RGB1.wB >> 7;
    w2 = RGB2.wB >> 7;
    w3 = RGB3.wB >> 7;
    w4 = RGB4.wB >> 7;
    lpRGBOut->wB = (WORD)(((w1 * dwTemp1) >> 16) +
                        ((w2 * dwTemp2) >> 16) +
                        ((w3 * dwTemp3) >> 16) +
                        ((w4 * dwTemp4) >> 16));
    //Note:  We leave the results in the lower 8 bits to simplify
    //        the pixel display by calling procedure.
    // compute G
    w1 = RGB1.wG >> 7;
    w2 = RGB2.wG >> 7;
    w3 = RGB3.wG >> 7;

```

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```
w4 = RGB4.wG >> 7;
lpRGBOut->wG = (WORD)(((w1 * dwTemp1) >> 16) +
                      ((w2 * dwTemp2) >> 16) +
                      ((w3 * dwTemp3) >> 16) +
                      ((w4 * dwTemp4) >> 16));
// Note: We leave the results in the lower 8 bits to
//       simplify the pixel display by calling procedure.
// compute R
w1 = RGB1.wR >> 7;
w2 = RGB2.wR >> 7;
w3 = RGB3.wR >> 7;
w4 = RGB4.wR >> 7;
lpRGBOut->wR = (WORD)(((DWORD)w1 * dwTemp1) >> 16) +
              (((DWORD)w2 * dwTemp2) >> 16) +
              (((DWORD)w3 * dwTemp3) >> 16) +
              (((DWORD)w4 * dwTemp4) >> 16));
// Note: We leave the results in the lower 8 bits
//       to simplify the pixel display by calling procedure.
}
```